Human-Shark interactions: the case study of Reunion Island in the South-West Indian Ocean

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Abstract

An uncommon series of shark attacks, mostly involving surfers, occurred on the West coast of Reunion Island between 2011 and 2013, causing eight deaths. Following these events, which resulted in social, economic and political upheaval, and referred to as the "shark crisis", a scientific program with the aim of understanding shark behavior and ecology in Reunion Island was launched in 2012. It integrated spatial and temporal monitoring protocol of coastal uses allowing for the study of shark attack repercussions on the dynamics of 15 types of uses. In this paper, we bring shark and users observations together in order to assess human-shark interactions. Firstly, we assess the impacts that shark attacks have triggered in terms of users spatiotemporal distribution between 2011 and 2013. Secondly, we explore human-shark interactions in 2013 using cross-mapping techniques. Results show that three areas (*Saint-Gilles, Trois-Bassins, Etang-Salé*) have high levels of potential interaction and should be of high interest for the local authorities and stakeholders for further mitigation policies. Although further studies are needed to better understand the link between shark presence and shark attack, this study provides a first insight into human-shark interactions in Reunion Island.

Keywords : Human-Shark conflict; Shark attack; Risk mitigation policies; Recreational uses; MPA governance

1. Introduction

As the human population increases, there is an increasing need for land settlement, both for agriculture and recreational use (Stoate et al., 2001; Henle et al., 2008). This causes a reduction in wild habitats triggering Human-Wildlife Conflicts (HWC) which have increased worldwide (Madden, 2004). These conflicts have both direct implications i.e. humans being injured or killed by wild animals (Löe and Röskaft, 2004), and indirect implications i.e. material and crop destructions, death of farm animals, decline in tourism or competition for resources or habitats (Patterson et al., 2004 ; Tsakem et al., 2015). Traditionally, the human response to this threat consists in setting up a lethal population control program on the involved species and modifying the habitat to avoid human-wildlife interactions (Liu et al., 2001). There has been a shift in human perception and mentality of human-wildlife interactions over the past decade (Treves et al., 2006), with a rising interest in new strategies involving a reduction of human-wildlife interactions and a conservation of the habitat. Thus, an increasing number of worldwide authorities integrate lethal and/or nonlethal control, research programs, communication and education programs to their management plans.

In marine ecosystems, human-shark interactions give rise to one of the most important HWC. In terms of shark attack rates, USA, Australia and South Africa rank among the most affected countries (Caldicott et al., 2001). Even when the risk of shark attack is very low, shark attack events trigger a state of fear in the local population and may have strong economic repercussions (Hazin et al., 2008). Historically, the first response to shark attacks has been to set up shark control programs as seen in Australia, Hawaii and South Africa. These shark control programs aim to mitigate shark risk by reducing the coastal shark population (Wetherbee et al., 1994; Dudley, 1997; Dudley and Simpfendorfer, 2006). More recently, where the main purpose of shark control programs has been to secure human activities, biodiversity conservation and research axis has also been integrated in order to better understand, characterize and quantify human-shark interactions. Thus, many authors stress the need to improve the knowledge of human perception and activities at a local scale in order to ensure an effective human-shark interaction management (Muter et al., 2013; Neff and Hueter 2013; Hazin and Alfonso, 2013; Gibbs and Warren, 2015).

In a conservation context such as a Marine Protected Area (MPA) network, it is assumed that a better understanding of the patterns of recreational uses is required for an effective management plan (Dwight et al., 2007; David et al., 2006; Thomassin, 2011). Thus, recreational uses surveys on coastal environments have been increasingly carried out over the last 10 years (Le Corre et al., 2011; Lemahieu, 2015). Despite a predominance of social disciplines, an increasing interest from marine biologists can be seen in relation to addressing the impact of scuba diving (Rodgers and Cox, 2003; Zakai and Chardwick-Furman, 2002), swimming (Cambert et al., 2007), boating pollution (Warnken and Leon, 2006) and global recreational uses (Liu et al., 2012). Uses surveys are carried out in order to develop some performance indicators (Veiga et al., 2010 ; Alós and Arlinghaus, 2012 ; Smallwood et al., 2012) to optimize the tourism potential of these natural areas (Brigand et al., 2005; Robert et al., 2008), coastal lands planning (Breton et al., 1996), or more rarely, to optimize water quality (James, 2000 ; Turbow et al., 2003) or bathing security services (Dwight et al., 2007 ; Harada et al., 2011). Nevertheless, no studies were carried out as a contribution to shark attack mitigation policies.

In Reunion Island, a French overseas territory located in the Western Indian Ocean, shark attacks occurred at a rate of 1.23 per year between 1980 and 2011 (Squal'idées, unpublished data). The bull shark (*Carcharhinus leucas*) and the tiger shark (*Galeocerdo cuvier*) were the two species commonly involved in these attacks (Gauthier, 2012). In 2011, following a series of 6 shark attacks along the west coast, of which two were fatal, local authorities officially recognized the Human-Shark Conflict (HSC) by referring to it as a "shark crisis". Since then, this new HSC has had economic, social, ecological and political impacts on the island (Fabing, 2014; Jaccoud, 2014; Taglioni and Guiltat, 2015). Facing the lack of knowledge on shark behavior, a shark research program called CHARC[1] devoted to the study of bull and tiger shark behavior along the west coast was launched at the end of 2011. To promote a systemic and integrated approach, the program integrated an existing marine uses monitoring protocol. This uses monitoring survey has been carried out annually since 2010, feeding the local MPA pressure and governance indicators (Lemahieu, 2015).

The aim of this study is to explore human-shark interactions by bringing the spatial patterns of shark presence and human uses together. We first mapped the shark attacks which occurred between 2011 and 2013 and put it against the 2010-2013 spatial uses evolution maps. Therefore, we were able to evaluate how shark attacks impacted spatial and temporal uses distribution patterns over time. Finally, 2013 shark presence data was spatially mapped against 2013 uses distribution to assess human-shark interactions and discuss research contribution into shark attack mitigation policies strategies.

2. Materials and methods

2.1. Study area

Reunion Island is a two million-year old volcanic island located in the south-western Indian Ocean. The 2512 km² island has a 12 km² fringing reef belt on its West coast. The study area stretched over a 44 kilometer coast from *Saint-Paul* to *Etang-Salé* within the MPA perimeter, which was created in

[1] Connaissances de l'écologie et de l'HAbitat de deux espèces de Requins Côtiers sur la côte ouest de La Réunion

2007. The MPA management zoning is comprised of 115 area grids of an average size of 30 ha, based on geomorphologic homogeneity criteria, and demarcated *in situ* by yellow buoys and coastal benchmarks (figure 1).

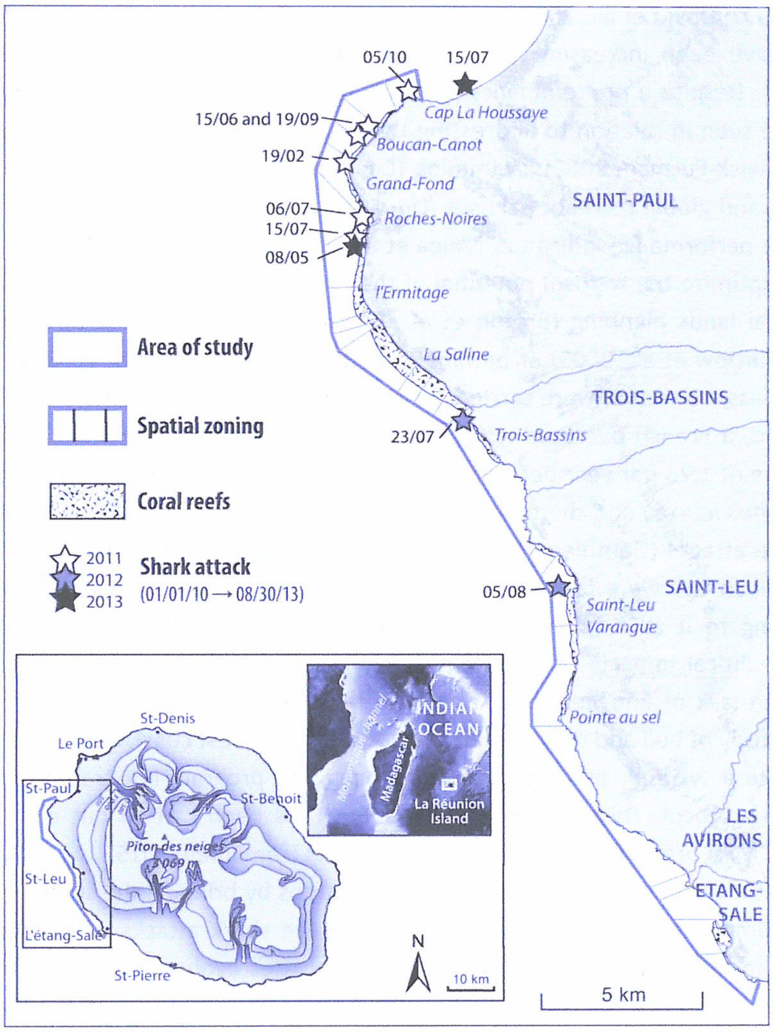

Figure 1. Study site location, spatial zoning and distribution of 2011, 2012 and 2013 shark attacks

2.2. Shark attack data

Shark attack data was extracted from the Reunion Shark Attack File (Squal'Idées, unpublished data). We selected only unprovoked shark attack from 01/01/2010 to 08/30/2013 in the MPA perimeter and its surroundings. An unprovoked shark attack is defined as physical contact between a human and a shark causing injury or death to the person or damage to their equipment with no human provocation of the shark. Human-shark interactions that did not result in injury or damage (e.g. shark encountering/spotting) were not taken into account.

In 2011, six shark attacks occurred in the northern areas of the MPA (figure 1). Apart from an attack on the 15th of July, which involved a kayaker, they all involved surfers. Most of the shark attacks occurred during austral winter (May-October), except one which occurred during summer (19th of February). The year 2012 was marked by two attacks on surfers at two very popular surf spots during the austral winter. A first fatal shark attack occurred on the 23th of July at *Trois-Bassins pass* and a second non fatal attack on the 5th of August at *Saint-Leu*.

In 2013, two fatal shark attacks were recorded during austral winter, one at *Ermitage nord* (*Brisants spot*) on a bodyboarder and a second in *St Paul Bay* on a young swimmer. We considered the latter in this study because of its proximity to the study area and its potential influence on users distribution.

2.3. Shark surveys

Acoustic telemetry

Shark presence data were recorded within the CHARC program framework which ran from December 2011 to April 2015. The program mainly focused on bull shark habitat use along the West coast of Reunion Island, using passive acoustic telemetry (Voegeli et al., 2001). Thirty-four adult bull sharks were tagged with 3 types of VEMCO acoustic tags, either a V16TP-4H (battery life of 845 days) or a V16-5H (battery life of 482 days) or a V13TP (battery life of 806 days, see table A.1). Detailed shark fishing and tagging methods are described in Blaison et al. (2015).

Shark presence along the West coast of Reunion Island was studied from November 2012 to June 2015 through a network of 36 underwater receivers of which 24 were within the study area (table A.1 and figure 6). Receivers' detection limits ranged from 200 to 400 meters. Receivers were removed from the water 4 times a year to allow for datasets to be downloaded onto computers using VUE software (VEMCO Ltd.)

Shark presence and data analysis

Shark detection data in 2013 were gathered on receivers located within the MPA perimeter. Detections were grouped into a "visit" or "time of presence[2]" (=Continuous Residence Time; Otha and Kakuma, 2005) according to data process analysis from Robert (2012). The Maximum Blanking Period (MBP[3]) was fixed at 1 hour similarly to other fine-scale studies and the Minimum Residence Time (MRT[4]) at 120 seconds (Capello et al., 2012; Dagorn et al., 2007) .

The number of shark detections compared to the number of detectable sharks (i.e. shark with a tag still emitting acoustic signal) was expressed in percentage. As all receivers were not deployed at the same time, the number of visits and the sum of presence (in days) were weighted by the number of deployed days for each receiver. These new indices allowed taking into account the spatial and temporal variations in the residual number of tagged sharks and deployed receivers. A Principal

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[2] A visit is defined as the time during which a tagged shark is continuously detected on a specific receiver.

[3] The MBP is the maximum time that may exist between two successive detections for it constitutes a single visit. Beyond this period, the first detection is the end of a visit and the next detection initiates a new one.

[4] The MRT is the minimum time allowed between two successive detections from a same tag on a specific receiver for it constitutes a visit. The MRT is usually close to the tag pulse interval.

Component Analysis was performed on the 24 receivers and the 5 shark presence variables (i.e. the number of visits, the sum of presence, the number of detected sharks, the mean and the coefficient of variation of the time of presence). A Hierarchical Ascending Classification (HAC) with a Ward aggregation method was performed from the PCA factorial data using Statistica 6.1 software (StatSoft, Inc.) to investigate the shark presence within the study area. The number of groups was computed using the graph of melting levels. Values of each variable were compared between groups using the Kruskal–Wallis non-parametric analysis of variance. Non-parametric multiple comparison tests (post hoc Duncan tests) were carried out when significant differences were found. Following these results, each variable in each group was characterized by a discrete 4 ranges scale: low, medium, high and very high. Finally, shark presence was classified using the same approach i.e. low when all variables are low; medium when variables are low or medium; high when variables are high or very high; and very high when all variables are very high.

2.3. Coastal uses surveys

Sampling methods

Given the extensive size of the MPA (44 kilometers long) and the strong users density per surface unit expected (Cazes-Duvat and Pesme, 2002; Mirault, 2006), the methodological choice turned to aerial surveys using a camera. One hundred forty nine flights were performed using a three axis Raus S7 courier at a speed of 90 km/h and at a minimum altitude of 300 meters above the sea surface. On the way out, observations on fore-reef and reef zones were directly reported on a map and a camera was used to "freeze" activities located on the coastal strip, the back reef and reef on the return. One year sample would consist in sharing equally 42 to 48 flights (depending on the year), between mornings (10:00) and afternoons (15:30), austral summer and austral winter, weeks and week-ends, holidays and scholar periods. Considering these criteria, flights were evenly scheduled over the sampling period. Initially, 14 types of uses were listed (Mirault, 2006) and monitored (Lemahieu, 2015) over the 2010-2012 period. In 2013, a new survey campaign was funded by the CHARC program in order to better understand the impact of shark attacks on spatial and temporal dynamics of users distribution. Twenty five flights were carried out twice a week at 15:30, with one taking place on a week day and the other on a week-end day.

In the context of the "shark crisis", this publication focuses on uses which have been historically vulnerable to shark attacks, namely surfing, swimming, snorkeling or paddleboarding.

Users distribution and data analysis

The number of users was counted on photos after each mission and counts were entered in an Excel database according to the grid area of reference. The 115 areas ID facilitated data export to ArcGIS 10.2 software to enable statistical and spatial analysis. To ensure data homogeneity and consistency over time, only data collected during afternoon sampling was used for analysis. Since the shape and size of the grid areas are different, users presence was expressed as the number of users per coastal linear kilometer (users/kml).

All the uses considered as being vulnerable to shark attacks, due to their historical involvement in shark attacks (i.e. swimming, some nautical activities and surfing) were averaged, weighted to coastal length, and mapped. The same operation was reproduced with surfing as it raises the greatest concern in relation to shark attack exposure. 2010-2013 time series data were used to assess surfing, swimming, snorkeling and paddling evolution over time. The mean of users per year and standard deviation were put against the global average number of users for the year using plots. In order to cross map shark presence and human activity, we only considered areas of potential interaction. As a result, shallow reef areas were excluded. We built four classes based on Jenks natural breaks classification method. Classes were then discretized into qualitative classes by codifying the activity from "low" to "very high" in order to harmonizing both shark presence and uses data.

2.4. Human-shark interactions

Firstly, shark attacks and the evolving pattern of users were compared for the period between 2010 and 2013 in order to investigate the potential impact of shark attacks on users distribution over time. Secondly, shark presence and users presence in 2013 were brought together and mapped to assess spatial interactions between users and sharks. Buffer zones of 400 meters corresponding to the range of detection were calculated around the receivers using ArcGIS 10.2. The cross-mapping operation was done by intersecting both shark presence buffer zones and users presence areas layers. The resulting layer highlighted areas of interactions. The classification of those areas according to the level of interaction was done using a contingency table in which the same weight is given to both shark and users variables. A three groups classification was obtained, ranging from "low" to "high".

3. Results

3.1. Shark presence in 2013

In 2013, there were 37 607 detections of tagged bull sharks coming from 23 of the 34 tagged sharks. The 11 other tagged sharks were never detected during this period. From these detections, 4094 visits were calculated from 20 tagged bull sharks. The remaining three detected bull sharks did not stay in the network of receivers within the minimum amount of time required to generate a visit. We identified four main groups from The Hierarchical Ascending Classification based on the number of visits, the sum of presence, the number of detected sharks, the mean and the coefficient of variation of the time of presence all together (figure 2).

The first group includes nine receivers where recorded shark presence was "low" resulting from low values for all variables. The second group is composed of 8 receivers which detected a "high" shark presence with the higher number of shark detected and a "medium" number of visits. The third group includes four receivers for which shark presence was "medium" with a "medium" number of shark detected and a "medium" mean of the time of presence. In addition, this group is the only one with significantly high standard deviations for the time of presence. The fourth group integrates two receivers, gathering areas of "very high" shark presence resulting from very high values for all variables excluded standard deviations for the time of presence. The receiver "Grande Ravine" (receiver n°13, see table A.2) was not included in the global analysis as the data contained a very extreme value: a single shark was detected on the 27^{th} of December 2013 and stayed for 33 hours. Except for this particular event, all variables in this receiver were low during the study period.

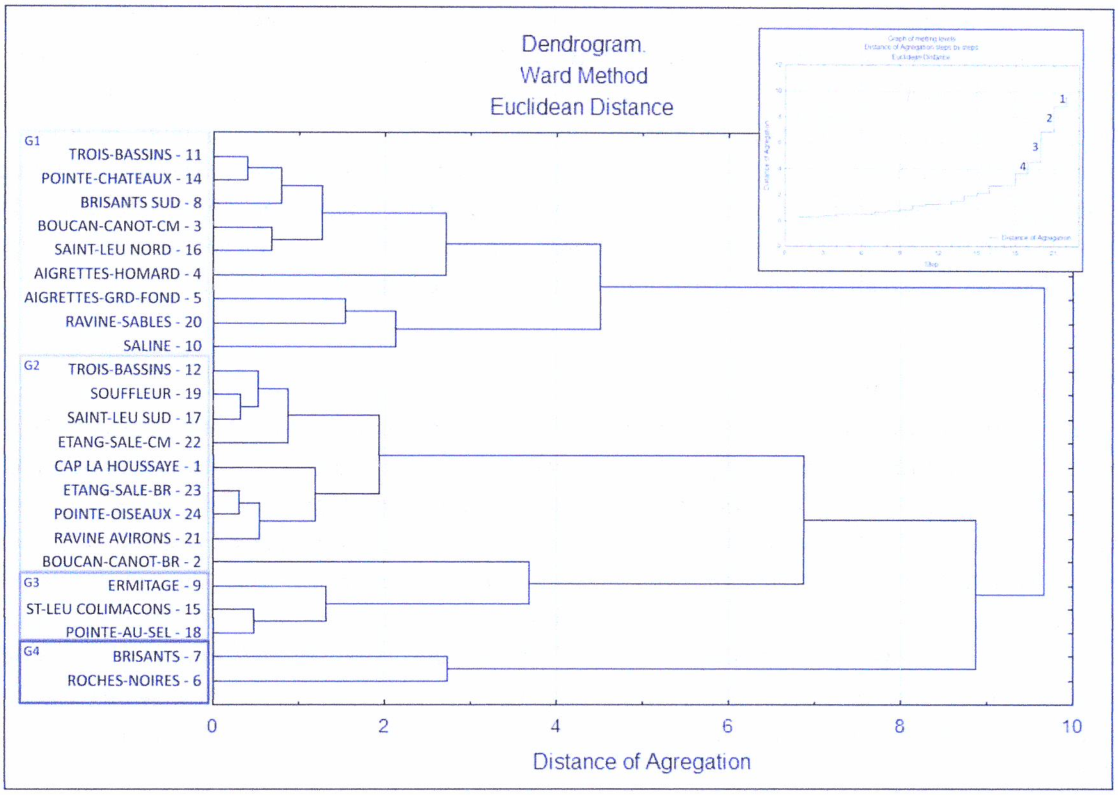

Figure 2: Dendrogram showing groups of receivers based on variables of shark presence (GX: Group number X) and graph of melting levels with the number of groups. Statistica 6.1.

3.2. Uses evolution patterns

In 2010, the spatial distribution of uses shows a heterogenic distribution of users (figure 3). This heterogeneity was demonstrated and interpreted for 14 uses in a previous articles dealing with all of the 14 uses monitored (Lemahieu et al., 2013). *Ermitage* (1027 users/kml for *Ermitage Sud sanctuaire*) and *Saline* (307 users/kml for *Saline Nord*) represent 24.6 % of the cumulated observations. *Boucan-Canot* and *Roches-Noires* northward also have a high average number of users, with 119.8 users (161.9 users/kml) and 42.8 (173.3 users/kml) users in 2010 (figure 3).

In 2011, six shark attacks occurred in the northern areas. The evolution of uses between 2010 to 2011 is marked by an increase of users on reef-protected sectors i.e. *Saline Nord* (+10.6 %), *Saline Trou d'eau* (+13.3 %) and *Saline Sud* (+16.2 %). In contrast, an important decrease of activity is noticeable in the northern spot of *Boucan-Canot* (-35 %) (figure 3). In parallel, between 2010 and 2011, this area was subjected to a decrease of activity (-27 % in average), decreasing to -37 % of surfers in *Grand-Fond* area (dropping from 10.6 to 6.7 surfers/kml)(figure 4). Simultaneously, the average number of surfers in *Ermitage pass*, *Trois-Bassins pass*, *Saint Leu* sectors and *Etang-Salé* sectors increased (+155 %, +16 %, +25 % and +29 %) (figure 4).

In 2012, two shark attacks were recorded, one in *Trois Bassins pass* and one in *Saint Leu*. Meanwhile, between 2011 and 2012, the average surfing activities dropped by 98 % (0.20 surfers/kml) in northern areas, by 35.1 % in *Trois-Bassins pass* (6.9 surfers/kml) and by 31.7 % in *Saint-Leu sectors*. In *Etang Salé*, the decline is less significant (-14 %) (figure 4). The 2010-2011 increase tendency on reef-protected areas reaches *Ermitage* sector, with up to 31 % of increase on *Ermitage Sud Sanctuaire*.

Simultaneously, the activity decrease is very important in *Boucan-Canot* (-43.2 %) and *Roches-Noires* (-25.1 %) northern spots and in the central spot of *Saint-Leu* (-26.5 %) (figure 3).

In 2013, two other shark attacks happened, in *Brisants* and *Saint-Paul bay*, north outside to the study area. Between 2012 and 2013, the number of surfers dropped by 82 % in *Trois-Bassins pass* (1.2 surfers/kml), by 95 % in *Saint-Leu sectors* (0.3 surfers/kml) and by 50 % in *Etang-Salé* (10.6 surfers/kml) (figure 4). In parallel, the average number of users kept decreasing dramatically in *Roches-Noires* (-70.4 %) but initiated an increase in *Boucan-Canot* (+8.1 %). *Etang-Salé* sector was subjected to an important decrease of activity (-25 %). In contrast, the increase trend was maintaining itself in *Ermitage sanctuaire* (+27.4 %) and *Ermitage Sud sanctuaire* (+27.6 %) (figure 3).

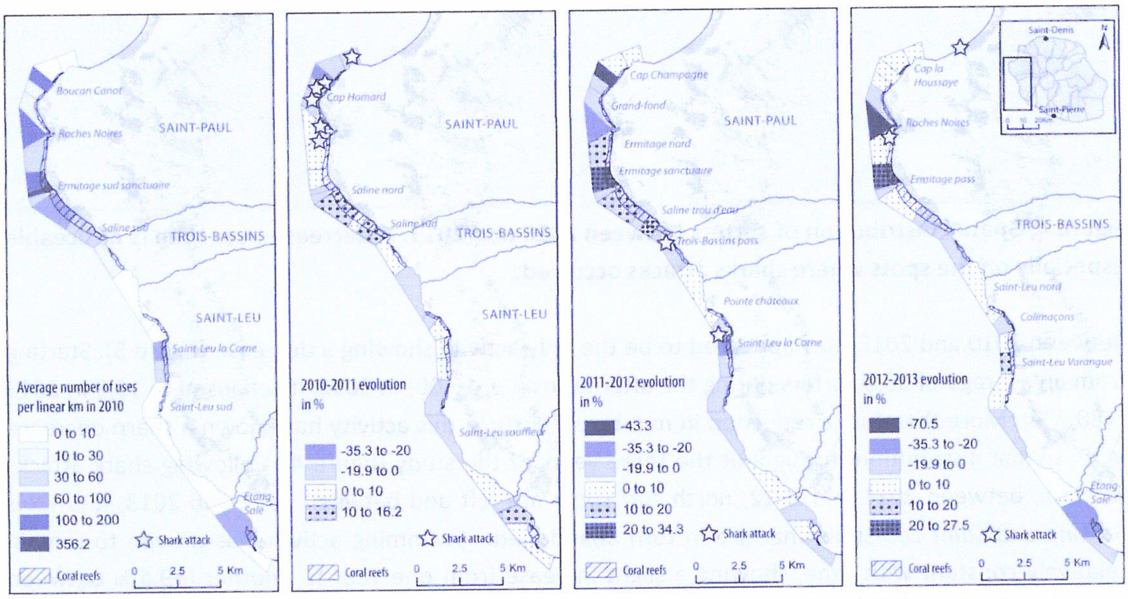

Figure 3. Spatial distribution of users (swimming, surfing, snorkeling and paddleboarding) and evolution over time (2010-2013) in percentage.

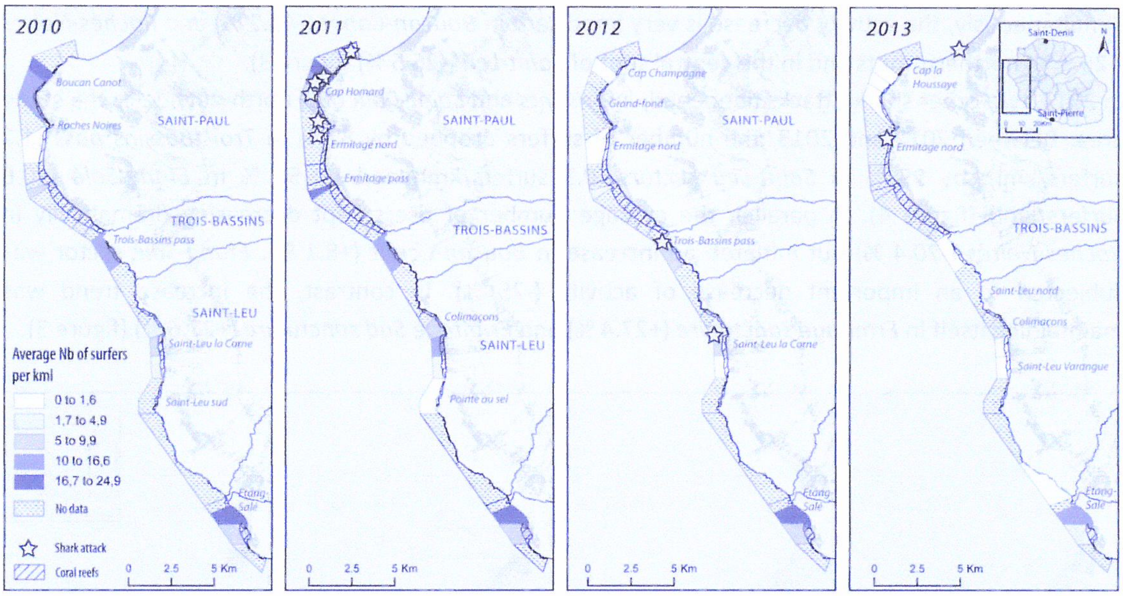

Figure 4. Spatial distribution of surfers between 2010 and 2013. A decrease over time is noticeable especially on the spots where sharks attacks occurred.

Between 2010 and 2013, surf appeared to be the only activity showing a decrease (figure 5). Starting from an average of 53,3 surfers during the afternoons (i.e. 16:00) in 2010, it collapsed to 19,9 in 2013 (- 80,7 %). More than just a reduction in number of surfers, this activity has known a sharp decrease in its spatial distribution throughout the three years of the study (figure 4). Following shark attacks location, between 2011 and 2012, north surf spots are left and between 2012 and 2013, it is *Trois Bassins* and *Saint Leu* spots that are in turn abandoned. Swimming activity has proven to remain relatively constant with time, showing a slight increase from one year to another (+9,4 % between 2010 and 2013). Conversely, some activities showed a durable increase from 2010 to 2013 i.e. paddleboarding and snorkeling. There were 15 times more observations of paddleboarders in 2013 (mean of 12,8 observations) than in 2010 (0,8 observation) (figure 5). The standard deviation of the average number of observations for swimming and paddleboarding also increased showing a rising variability of the practice over time.

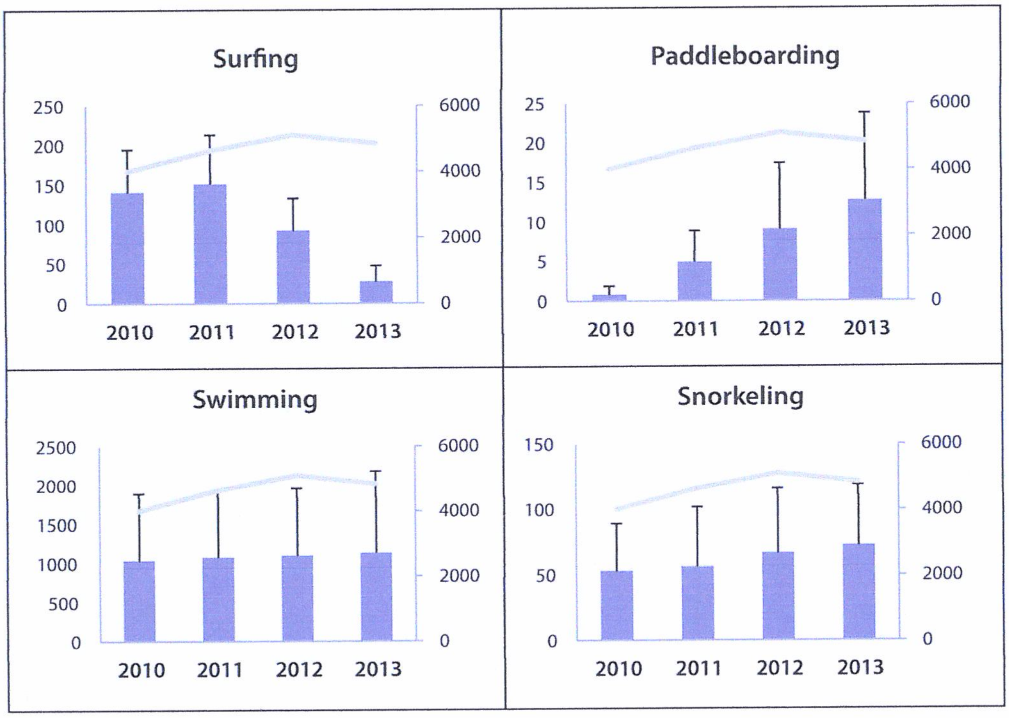

Figure 5. Temporal inter-annual evolution of the average number of users (and SD) per activity for surfing, paddleboarding, swimming and snorkeling uses, put against the average global number of users.

3.3 Human-shark interactions mapping in 2013

Areas of effective human-shark interactions in 2013 represent 12 % (450 ha) of the study area surface (figure 6). Areas of "high interaction" represent only 2.9 % (13 ha) of the total and are resulting from high level of shark and users presence. They are located in *Trois-Bassins* area (receiver n°12). Areas of "medium interaction" account for 48 % (216 ha) of the interaction areas and are equally distributed along the coastline. At *Roches-Noires*, *Trois-Bassins* (receiver n°11) area, *Saint-Leu Sud* and *Etang-Salé*, the medium level of interaction was resulting from a high to a very high presence of sharks and a low presence of users. At the opposite, on *Boucan-Canot* area (receiver n°2), the medium level of interaction is caused by the high level of activities rather than shark presence which proved to be low. Finally, areas of "low interaction" account for 49 % of interaction areas and are located in the northern area, at *Saint Leu Nord* and *Ravines des Sables*, resulting from a low to medium shark presence coupled with a low users presence (figure 6).

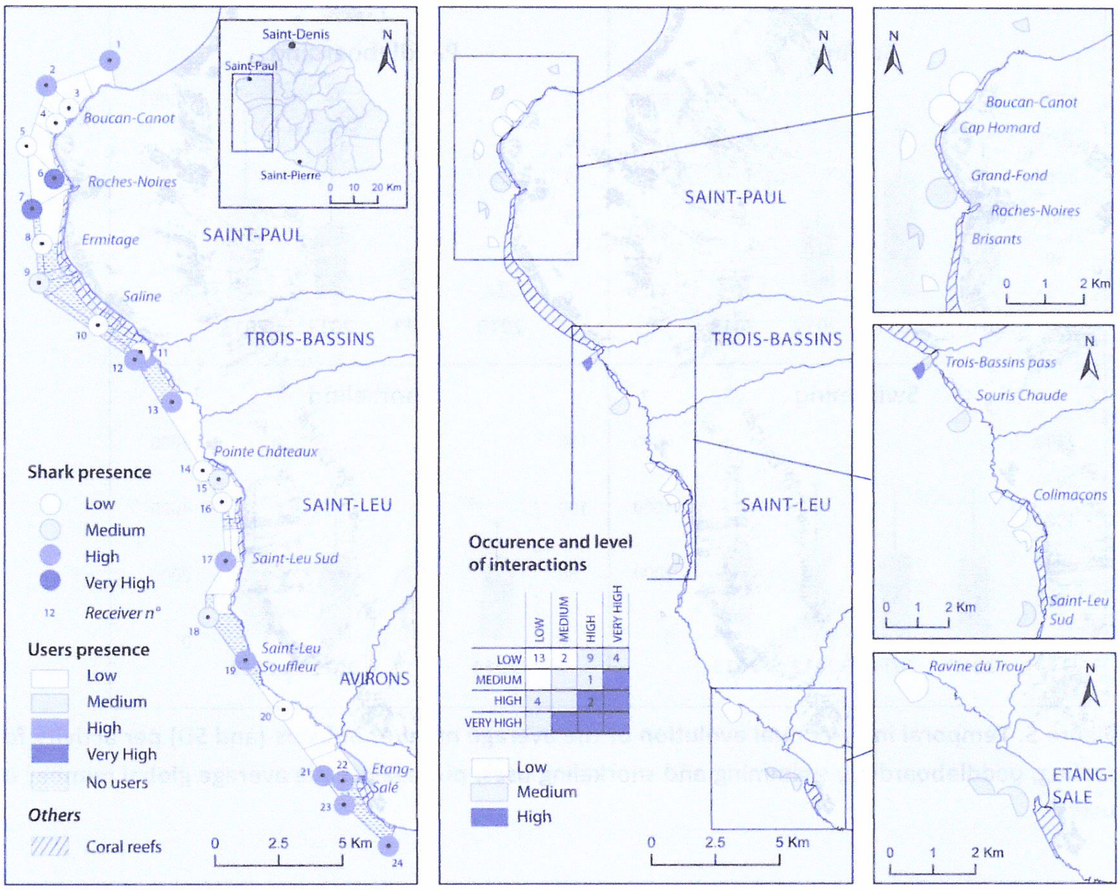

Figure 6 - Human-shark interactions in the MPA of Réunion Island in 2013. a. represents sharks and users presence overlap. b. represents the occurrence and level of human-shark interactions. Contingency table was built from the intersection counts and levels. Levels thresholds were designed regarding the distribution of occurrence in the table, and to ensure a good representativeness of effective interaction in 2013.

4. Discussion and Conclusion

Users distribution seems to echo shark attack distribution

According to our findings, the distribution of users observed over the period 2011-2013 seems to echo the distribution of shark attacks. The evolution of the distribution of users during 2010-2011 is characterized by a drop in attendance at the popular area of *Boucan-Canot*. Following the two shark attacks that occurred in this area, one in February and one in June, we hypothesize that the decrease in the presence of users most likely resulted from a climate of fear due to shark attack exposure. There was a third and fatal shark attack in this area in 2012 which led to the so called"shark crisis" Following these shark attacks in the area of *Boucan-Canot*, the government and municipality prohibited most marine uses through various prefecture and municipality directives. Thus, the important decrease observed in 2011-2012 can be explained not only by a stronger fear of shark attack, but also by the shark risk management and mitigation measures taken by the authorities which aimed to decrease human-shark interactions by reducing vulnerable marine uses. As a response to this trend, an increase of users in reef-protected areas, namely *Ermitage* and *Saline* reefs, was observed over the same period. Indeed, the areas characterized by shallow bathing waters and a reef-crest are well-suited to many activities such as snorkeling, swimming and paddleboarding because of their shallow waters and the weakness of currents which allow safe practice conditions. Despite the presence of a coral reef, *Saint-Leu* constituted an exception to this assessment since attendance fell by 20 % over the period. This change in the trend could be explained by the overflow of a sewage treatment plant in 2012 which made the water unfit for swimming over a long period and deteriorated coral reefs. Finally 2012-2013 evolution scores saw a stagnation, even a decrease of global attendance (-5.1 %) whereas the average number of bathers increased by 3.1 % (Lemahieu, 2015), questioning the notion of resilience after shark attacks. Over the same period, Saint-Leu reef appears to have become attractive again (+11 %), a trend which supports our hypothesis about the sewage overflow explaining the 2012 decrease. Similarly, we observe a gain in *Boucan-Canot* (+8.1 %), a trend that could be explained by the settlement of shark nets in the area during early 2013. These nets constitute a safety barrier separating users from open water areas, avoiding risk of human-shark interactions. On reef-protected areas, the increase tendency was constant between 2012 and 2013 on *Ermitage* but a decrease on *Saline* (down to -10 %) is noticeable. One possible explanation for this drop is that the remoteness of *Saline* reef crest, when compared to *Ermitage,* means that people may remain suspicious about possible shark presence. Finally, *Ermitage* enjoyed widespread media coverage as being a haven in the wake of the "shark crisis". This image of optimal safety conditions might well have contributed to its increased popularity.

The activity of surfing has historically been most implicated in shark attack events in Reunion Island (Lagabrielle et al., 2012; Taglioni and Guiltat, 2015). Its distribution over time and space seems to mirror the shark attacks distribution. The prevalent pattern consists in a shift and transfer of users from one spot to another following a shark attack. As the shark attacks chronologically occurred from the North towards the South, the same southward movement in surfing activity is observed. Consequently, we observed the rising popularity of *Etang-Salé* surf spots over the sampling period. This new trend likely result from its remoteness and distance to the spots affected by shark attacks. In 2013 though, similarly to most of uses we sampled, the surfing attendance in *Etang-Salé* started to decrease. We might attribute this trend to a popular belief of a North-South migration of sharks. It should be noted that a lethal shark attack occurred in *Etang-Salé* in October 2013, just after our sampling. By 2016, almost all surf areas on the west and south-west coast had been exposed to at least one shark attack in the preceding 5 years. A new sampling would bring new insights in allowing to observe spatial and temporal surfing dynamics as all spots are now considered to being exposed to shark attacks. In addition, new safety measures were taken in 2013 in *Boucan-Canot* and *Roches-Noires* where safety nets were expanded to allow surfing within the secured area or the deployment of underwater shark spotters. These new configurations may have contributed to modify the distribution of surfers but also their perception of shark attack exposure.

Human-shark interactions

The study of the spatial distribution of both sharks and users has highlighted three types of human-shark interaction areas: i) areas of low interaction resulting from various configurations of low to medium shark/users presence, ii) areas of medium interaction resulting from various configurations of medium to very high shark/users presence, iii) areas of high interaction resulting from various configurations of high to very high shark/users presence.

Areas with high and medium levels of interaction in 2013 correspond to areas historically involved in shark attacks. *Roches-Noires*, and more broadly the northern area of the study area accounted for 40 % of the shark attacks recorded between 2011 and 2013. In *Trois-Bassins* where human-shark interactions were high in 2013, a single fatal shark attack happened in 2012. In the high interaction area of *Etang-Salé*, no shark attack was recorded during the sampling period but two shark attacks occurred later in October 2013 and February 2015.

Unexpectedly, an interaction area of medium level with low shark presence is located at *Boucan-Canot* (receiver n°3), a spot where 2 shark attacks occurred in 2011. Some bias detected on the local acoustic telemetry devices provides a possible explanation for this outcome. Range tests on receivers deployed at *Boucan-Canot* showed a small range of detection in the area, mostly explained by the presence of reefs (Authors, unpublished data), which can degrade the acoustic signal from tags and explain why shark presence in this area could have been underestimated. Furthermore, it was showed that there is a seasonal variation of bull shark presence along the west coast of Reunion Island (Blaison et al., 2015). Given this observation, shark presence at *Boucan-Canot* could be attributed to variations from a high to low presence between seasons.

Some areas where shark attacks occurred were proven to correspond to areas of low interaction according to our analysis i.e., *Saint-Leu la Corne* (receiver n°16) and *Cap Homard/Aigrettes/Grand-Fond* (receivers n°4 & 5). Following these observations, we made the hypothesis that shark attacks wouldn't always be correlated to the number of sharks nor the time that sharks spent in a given area. Little is known about shark behavior response according to life cycle, i.e. mating, pupping, feeding, resting and travelling, but we assume that shark aggressiveness changes depending on its life cycle stage and/or its activity (Hobson 1963; Tricas and Le Feuvre, 1985; Pratt and Carrier, 2001).

Interpretation of medium interaction areas reveals the limitation of our method as shark presence and users variables were weighted equally. For instance, some areas of medium interaction such as *Grande Ravine* (receiver n°13) result from a high shark presence and a low users presence. Conversely, an area like *Boucan-Canot* (receiver n°3) is classified as being a medium interaction area for being highly frequented by users but poorly by sharks. Historical shark attacks have been recorded in this last area though (Taglioni and Guiltat, 2015). The high shark presence area nearby (receiver n°2) suggests that the shark presence may be higher in *Boucan-Canot* area than observed and so the level of interaction could have been underestimated. Future studies concerning the level of interaction between sharks and users in a specific location should thus consider shark presence in this particular location but also in its surroundings. The weighting of both human and shark presence variables should also be further questioned. Several authors addressed the role of both variables in encountering issues, and the global increase of users in recreational areas is believed to rather be the driving force behind shark attack frequency (Schultz, 1967; Kock and Johnson, 2006). However, some further research based on these assumptions are required to be able to define a proper weight to users presence variable in interaction assessments.

Mitigation policies/ A shark risk recognized and addressed by the local authorities

Over the last 5 years, the French Government, the Region and municipalities authorities have implemented several shark risk management measures in response to shark attacks. Parallel to CHARC, other programs funded by the French government, based on culling strategies aimed at assessing the presence of carcharotoxin (Ciguatera I and II) and testing some fishing techniques to secure bathing areas (CapRequin I and II). Despite some authors pointing out the inefficiency of kill-based mitigation policies as an answer to Human-Wildlife conflicts (Treves et al., 2006), many countries still resort to this kind of mitigation policies. Lethal approach to reducing shark attacks have been reported in many countries including Australia (Crossley et al., 2014, Ferretti et al., 2015 and Gibbs and Warren, 2015), South Africa (Cliff and Dudley, 2011), New Zealand and Mexico (Gibbs and Warren, 2015), particularly where tourism and ocean use represent a major economic stake (Gibbs and Warren, 2015). As global awareness for biodiversity conservation has risen over these last few decades, we observe a progressive reduction of cullings, increasingly replaced by public education programs, shark hazard sensitization and beach protection program development (Curtis et al., 2012). These changes sometimes contribute to make human-wildlife conflicts evolve into conflicts between human and institutions (Hill, 2004), namely when various economic interests are mobilized and result in divergent interests and opinions about the way to mitigate human-wildlife interaction.

Currently, with the creation of a new resource center dedicated to shark risk (Centre de Ressources et d'Appui sur le risque requin), there is a willing to implement long-term measures to mitigate shark exposure. A variety of tools, including safety nets and underwater surveillance, were discussed and tested by authorities and stakeholder consortiums. So far, these mitigation methods have proven their effectiveness with no incident being reported in an area where the system was operational. However, they are often difficult to set up as they have high installation and maintenance costs. Furthermore, they have limited spatial coverage. Thus, it seems important to first identify priority areas to be equipped. This study provided spatial information on the level of interactions between users and sharks that could help local authorities to identify these areas. In addition to Boucan-Canot and Roches-Noires, we suggest that Trois-Bassins and Etang-Salé should be considered as priority areas. In a second phase, particular attention should be given to Saint-Leu (North and South).

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Supplementary materials

Table A.1- List of the tagged sharks

Date of tag deployment	Species	ID Code	Sex	Maturity	TL (cm)	Type of tag
18/12/2011	Bull shark	3	F	Adult	300	V16-5H
10/02/2012	Bull shark	11	F	Adult	314	V16-5H
10/02/2012	Bull shark	12	F	Adult	308	V16-5H
27/09/2012	Bull shark	14	F	Adult	310	V16TP-4H
28/09/2012	Bull shark	17	F	Adult	250	V16TP-4H
28/09/2012	Bull shark	18	F	Adult	329	V16TP-4H
28/09/2012	Bull shark	20	F	Adult	274	V16TP-4H
05/11/2012	Bull shark	25	F	Adult	314	V16TP-4H
22/11/2012	Bull shark	82	F	Adult	300	V16TP-4H
29/12/2012	Bull shark	28	F	Adult	310	V16-5H
06/01/2013	Bull shark	30	F	Adult	238	V16-5H
06/01/2013	Bull shark	31	F	Adult	305	V16-5H
10/01/2013	Bull shark	32	F	Adult	312	V16-5H
10/01/2013	Bull shark	33	F	Adult	308	V16-5H
06/02/2013	Bull shark	34	F	Adult	300	V16TP-4H
20/02/2013	Bull shark	5	F	Adult	260	V16TP-4H
27/02/2013	Bull shark	10	F	Adult	300	V16TP-4H
05/03/2013	Bull shark	15	F	Adult	290	V16TP-4H
24/03/2013	Bull shark	21	F	Adult	307	V16TP-4H
26/03/2013	Bull shark	84	F	Adult	325	V16TP-4H
25/02/2014	Bull shark	67	F	Adult	300	V16TP-4H
02/01/2012	Bull shark	4	M	Adult	250	V13TP
29/02/2012	Bull shark	23	M	Adult	240	V16-5H
24/06/2012	Bull shark	81	M	Adult	250	V16TP-4H
01/11/2012	Bull shark	24	M	Adult	290	V16TP-4H
05/11/2012	Bull shark	26	M	Adult	305	V16TP-4H
06/01/2013	Bull shark	29	M	Adult	308	V16-5H
20/02/2013	Bull shark	6	M	Adult	260	V16TP-4H
01/03/2013	Bull shark	13	M	Adult	269	V16TP-4H
15/03/2013	Bull shark	16	M	Adult	290	V16TP-4H
19/03/2013	Bull shark	19	M	Adult	260	V16TP-4H
24/03/2013	Bull shark	83	M	Adult	276	V16TP-4H
26/03/2013	Bull shark	22	M	Adult	294	V16TP-4H
08/09/2013	Bull shark	72	M	Adult	250	V16-5H

723 Table A.2 - List of the receivers (CM : Mooring; BR: MPA buoys)

Code	Name	Location	ID	Lat	Long	Bottom deth	Receiver depth	Structure
1	Cap La Houssaye	Large	109256	-21.009577	55.238278	48.0	18.7	BR
2	Boucan Canot BR	Large	109269	-21.018239	55.214268	55.0	18.0	BR
3	Boucan Canot CM	Coastal	109277	-21.026260	55.222790	20.6	20.6	CM
4	Aigrettes-Homard	Coastal	109271	-21.034170	55.214970	21	21	CM
5	Aigrettes-Grd-Fond	Large	101965	-21.039500	55.206600	51.5	16.8	BR
6	Roches Noires	Coastal	119589	-21.051083	55.216833	17.0	16.0	BP
7	Brisants	Large	109267	-21.061667	55.208333	38.6	18.8	BR
8	Brisants Sud	Large	119615	-21.074006	55.211982	30.0	16.0	BR
9	Ermitage	Large	119596	-21.087670	55.210792	41.0	16.5	BR
10	Saline	Large	112940	-21.102791	55.232843	17.0	14.0	BR
11	Trois Bassins CM	Coastal	119592	-21.112365	55.248706	21	21	CM
12	Trois Bassins BR	Large	119608	-21.114949	55.246506	42.8	16.4	BR
13	Grande Ravine	Coastal	119607	-21.129963	55.260295	19.6	19.6	CM
14	Pointe Chateaux	Large	119606	-21.154523	55.271751	21.7	15.0	BR
15	St-Leu Colimaçons	Coastal	112937	-21.157541	55.277703	19.0	17.7	BR
16	Saint-Leu Nord	Large	112942	-21.161664	55.277042	25	25	CM
17	Saint-Leu Sud	Large	112945	-21.186267	55.279907	49.6	16.8	BR
18	Pointe-au-Sel	Large	119601	-21.205959	55.273157	97.0	31.7	BR
19	Souffleur	Coastal	119612	-21.221361	55.286972	20	19	CM
20	Ravine Sables	Coastal	119611	-21.239361	55.301139	20	19	CM
21	Ravine Avirons	Large	119590	-21.262607	55.315752	33	30	BR
22	Etang-Salé-CM	Coastal	119588	-21.264583	55.32325	8	7	BP
23	Etang-Salé-BR	Large	119586	-21.273099	55.323640	44	17	BR
24	Pointe-oiseaux	Large	119591	-21.287811	55.340051	41	18	BR

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